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METHODS FOR INCREASING THE ENERGY-EFFICIENCY OF GLASS FURNACES

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Methods for increasing the heat efficiency of commercial glassmaking are examined for the example of an analysis of the heat-balance in glass furnaces with a horseshoe flame. It is shown that it is possible to develop container-glass furnaces with world-class energy efficiency.

Key words: glass furnace, energy efficiency, heat balance.

The energy efficiency of glass furnaces is determined by the specific heat consumption per 1 kg melt:

$$q_{\mathrm{sp}} = \frac{BQ_{\mathrm{low}}^{\mathrm{w}} + Q_{\mathrm{elec}}}{P_{\mathrm{fc}}}, \tag{1}$$

where q_{sp} is the specific heat consumption, kJ/kg; B is the fuel consumption rate, $\mathrm{m^3/sec}$; $Q_{\mathrm{low}}^{\mathrm{w}}$ is the lower working calorific value of the fuel, $\mathrm{kJ/m^3}$; P_{fc} is the furnace capacity, kg/sec; and, Q_{elec} is the electric heating power ($Q_{\mathrm{elec}} = 0$ for a flame furnace), kW.

In world practice, the highest energy efficiency of container glassmaking was achieved in regenerative furnaces with a horseshow flame: $q_{\mathrm{sp}} \approx 3.85 - 4.33$ MJ/kg (920 – 1035 kcal/kg). Domestically manufactured furnaces are characterized by considerably higher specific heat consumption for glassmaking. For this reason, the most important problem facing the industry is to increase the energy efficiency of furnaces. Its urgency is especially evident in the present environment of increasing natural gas and electricity prices.

We shall examine the conditions under which world-level energy efficiency of industrial glassmaking is attained for the example of a regenerative flame furnace ($Q_{\mathrm{elec}} = 0$).

In its general form the equation of heat balance in the working space of a continuous, flame, glass furnace (heat accumulation in masonry $Q_6 = 0$) heated by gas or liquid fuel (the underburning of solid fuel $Q_4 = 0$) has the form

$$Q_{\mathrm{chem}} + Q_{\mathrm{p.air}} + Q_{\mathrm{p.f}} = Q_{1.1} + Q_{1.2} + Q_2 + Q_3 + Q_5 + Q_{\mathrm{negl}}, \tag{2}$$

where $Q_{\mathrm{chem}} = BQ_{\mathrm{low}}^{\mathrm{w}}$ is the chemical heat of the fuel, kW; $Q_{\mathrm{p.air}} = Bc_{\mathrm{a}} t_{\mathrm{a}} L_{\alpha}$ is the physical heat of heated air, kW; $Q_{\mathrm{p.f}} = Bc_{\mathrm{f}} t_{\mathrm{f}}$ is the physical heat of the fuel, kW; $Q_{1.1}$ is the heat consumption for glassmaking, kW; $Q_{1.2} = c_{\mathrm{mg}} \bar{t}_{\mathrm{mg}} P_{\mathrm{loss}}$ are the heat losses with the production melt flow, kW; $Q_2 = Bc_{\mathrm{s}} t_{\mathrm{s}} V_{\alpha}$ are the heat losses with the products of fuel combustion, kW; $Q_3 = 0.02BQ_{\mathrm{low}}^{\mathrm{w}}$ is the chemical underburning of the fuel, kW; $Q_5 = \sum_{i=1}^{n} F_i \bar{K}_i (\bar{t}_{\mathrm{int}\,i} - t_{\mathrm{sur}}) + \sum Q_{\mathrm{rad}}$ are the heat losses by heat conduction through the masonry and by radiation through the burner inlets, doghouse roofs, and closed observation windows (2nd term), kW; $Q_{\mathrm{negl}} = 0.1(Q_1 + Q_3 + Q_5)$ are the neglected heat losses; c_{a}, c_{f}, and c_{s} are the specific heat capacity of air, fuel, and smoke, respectively, $\mathrm{kJ/(m^3 \cdot K)}$; t_{a}, t_{f}, t_{s}, and t_{sur} are the temperature of the air, fuel, smoke (at furnace exit), and surroundings, respectively, °C; $\bar{t}_{\mathrm{mg}}$ is the average temperature of the molten glass at the entrance into the channel, °C; c_{mg} is the specific heat capacity of the molten glass at $\bar{t}_{\mathrm{mg}}$, $\mathrm{kJ/(kg \cdot K)}$; L_{α} and V_{α} are the flow rate of the air and smoke for the actual air flow rate coefficient ($\alpha = 1.1$), respectively, $\mathrm{m^3/m^3}$ gas; F_i is the area of the ith surface of the furnace masonry, $\mathrm{m^2}$; $\bar{K}_i$ is the average coefficient of heat transfer through the ith surface of the masonry, $\mathrm{W/(m^2 \cdot K)}$; $\bar{t}_{\mathrm{int}\,i}$ is the integral average internal temperature of the ith surface, °C; and, n is the number of barrier surfaces of the melting part of the furnace.

The coefficient of heat transfer is determined by the structure of the masonry of the furnace barriers and the thermal conductivity of the refractory and heat-insulation materials:

$$\bar{K}_i = \frac{1}{\sum_{j=1}^{k} \frac{S_j}{\lambda_j} + \frac{1}{\alpha_{\mathrm{out}\,i}}}, \tag{3}$$

where S_j and λ_j are the thickness and thermal conductivity of the jth layer of the masonry, m, $\mathrm{W/(m \cdot K)}$, respectively;

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$\alpha_{\mathrm{out}i}$ is the coefficient of heat emission on the outer ith barrier surface of the furnace, $\mathrm{W/(m^2 \cdot K)}$; and, k is the number of masonry layers.

The heat consumption for glass formation is calculated from the relation

$$Q_{1.1} = P_{\mathrm{fc}}\,[G_{\mathrm{bat}}(q_\Sigma + q_{1.1} + q_{1.2} + q_{1.3}) - q_{\mathrm{bat}}], \tag{4}$$

where G_{bat} is the consumption of batch per 1 kg molten glass, kg/kg; q_Σ is the total heat effect of the glass-formation reactions per 1 kg batch, kJ/kg; $q_{1.1}$, $q_{1.2}$, and $q_{1.3}$ are the heat losses to evaporation of moisture, heating of the products of degasification, and glass melting, respectively, kJ/kg; and, q_{bat} is the physical heat content of the batch and cullet, kJ/kg molten glass.

We shall rewrite Eq. (2) for Q_{chem}, expand the content of the principal items in the heat balance, and substitute the new expression into the relation (1). The resulting equation

$$q_{\mathrm{sp}} = \frac{1{,}1(Q_{1.1} + c_{\mathrm{mg}}\bar{t}_{\mathrm{mg}}P_{\mathrm{fc}} + Q_3 + Q_5)}{P_{\mathrm{fc}}} + \frac{B(c_{\mathrm{s}}t_{\mathrm{s}}V_\alpha - c_{\mathrm{a}}t_{\mathrm{a}}L_\alpha - c_{\mathrm{f}}t_{\mathrm{f}})}{P_{\mathrm{fc}}} \tag{5}$$

makes it possible to perform a detailed analysis of the factors determining the energy efficiency of glass furnaces.

The quantity $Q_{1.1}$ is a constituent part of the theoretical minimum of the heat consumption for glassmaking. For a batch with 4% moisture, 30% cullet, and heating temperature 40°C, the specific energy consumption for glassmaking is $Q_{1.1}/P_{\mathrm{fc}} \approx 906$ kJ/kg. The enthalpy of 1 kg melt is independent of the furnace design and is an irreducible item of energy consumption.

The quantity $Q_{1.2}/P_{\mathrm{fc}}$ can be associated to the theoretical heat consumption on glassmaking provided that $\bar{t}_{\mathrm{mg}}$ does not exceed the melting temperature t_{prod} in the feeder. In reality $\bar{t}_{\mathrm{mg}} - t_{\mathrm{prod}} > 100$°C. For this reason, the molten glass in the distribution channel is force-cooled to the production temperature. And, depending on the furnace capacity, the heat losses into the surroundings which are not due to the technological process can reach 500 – 1000 kW.

For container glass, the melt temperature at production corresponds to viscosity 10^2 Pa · sec. Approximately, $t_{\mathrm{prod}} = 1200$°C. Therefore, only a portion of the heat losses with the production flow can be substantiated theoretically: $Q_{1.2}/P_{\mathrm{fc}} = c_{\mathrm{mg}}t_{\mathrm{prod}} \approx 1434$ kJ/kg. Overall the theoretical minimum heat consumption for glassmaking is $906 + 1434 = 2340$ kJ/kg. The difference between the actual and theoretical specific heat consumption is non-productive energy consumption, minimizing which is the main problem of designing glass furnaces.

It follows from Eq. (5) that the furnace design largely determines the energy efficiency of the glassmaking process. The application of theoretically validated design solutions makes it possible to realize in practice conditions under which rational values of the quantities $\bar{t}_{\mathrm{mg}}$, t_{a}, t_{s}, and Q_5, which together determine technical efficiency of the furnace, can be secured.

The high temperature of the molten glass at the exit from the tank is one of the problems of high-capacity glassmaking. Thus far, no effective method of controlling the heat content of the production flow has been found. On the applied level it is helpful to use the experimental expression given in [1], which establishes a relation between $\bar{t}_{\mathrm{mg}}$ and the specific amount of molten glass extracted:

$$\bar{t}_{\mathrm{mg}} = 1410.3 - 28.385P_{\mathrm{sp}} + 1.0486P_{\mathrm{sp}}^2, \tag{6}$$

where P_{sp} is the specific extraction of molten glass, $\mathrm{tons/(m^2 \cdot day)}$.

We obtain from Eq. (6) that increasing the specific extraction of molten glass from 1 to 3 $\mathrm{tons/(m^2 \cdot day)}$ decreases the melt temperature at the tank exit from 1383 to 1335°C. It should be noted that the temperature of the production melt flow can be lowered by making a rational choice of the design parameters of the melting tank. Together with high specific extraction of molten glass, structural improvement of the convection flows makes it possible to attain $\bar{t}_{\mathrm{mg}} = 1290 - 1300$°C.

One of the main design requirements for a glass furnace is that the air heating temperature for combustion must be high. In energy-efficient furnaces, $t_{\mathrm{a}} \geq 1300$°C. In this case, the fraction of the physical heat content of air in the inflow part of the heat balance reaches 35%.

It is well known that the heating temperature of air in the regenerator is determined mainly by the heating surface area of the checkers F_{ch} and the heat content of the outgoing products of fuel combustion. Optimization of the external heat transfer in the working space of the furnace will substantially decrease the temperature of the smoke [1]. In furnaces with a horseshoe flame $t_{\mathrm{s}} \approx 1400 \pm 30$°C. For such a low smoke temperature, high-temperature air heating is achieved in regenerators characterized by the ratio $F_{\mathrm{ch}}/F_{\mathrm{mt}}$ (F_{mt} is the area of the melting tank of the furnace). In addition, when the regenerator masonry is designed the heat losses going into the surrounding environment must be reduced to a minimum. To decrease the amount of cold air sucked in, the external surfaces of the regenerator are sealed.

The design of the regenerator must be based on a detailed calculation of the regenerator heat exchange. At the stage where decisions are made about the arrangement, the empirical expression given in [1], whose correctness is confirmed by the practical data (Table 1), can be used to calculate the air heating temperature:

$$t_{\mathrm{a}} = 959.09 + 182.02P_{\mathrm{sp}} - 19.923P_{\mathrm{sp}}^2, \tag{7}$$

One of the most important methods of lowering the specific energy consumption for glassmaking is to minimize the heat losses going into the surrounding environment. It fol-

TABLE 1. Temperature Regime of a Single-Pass Regenerator of a Glass Furnace with a Horseshoe Flame

Furnace capacity, tons/day		256.0		224.3	
Specific throughput, tons/(m^2 · day)		2.50		2.19	
Gas flow rate, m^3/h		1400		1280	
Name of regenerator chamber		Left-hand chamber	Right-hand chamber	Left-hand chamber	Right-hand chamber
Control parameter		Temperature, °C			
Checkers top	Smoke	1314	1314	1280	1283
	Air	1291	1293	1257	1260
Checkers bottom	Smoke	443	448	409	401
	Air	147	134	135	152

TABLE 2. Heat Losses through the Structural Elements of the Melting Part of a Glass Furnace with a Horseshoe Flame [5 – 7]

Name of barrier surface	Heat flux through the heat-insulating part of the surface, W/m^2	Average heat flux, W/m^2
Working space of furnace:		
roof	816.8	1141.4
longitudinal walls	852.8	1751.6
end wall	852.8	1080.1
Melting tank bottom	–	1200.0
Melting tank walls (melting zone):		
cooled part of wall*	–	19056.5
discrete-insulation section	967.3	2626.0
continuous-insulation section	942.0	942.0
Melting tank walls (fining zone):		
cooled part of wall*	–	19588.6
discrete-insulation section	1016.2	2715.4
continuous-insulation section	965.3	965.3

* Air outflow velocity 50 m/sec.

lows from the data in Table 2 that multilayer heat insulation decreases the heat flux going into the surrounding environment by more than a factor of 1.5. The calculations show that the normative losses of heat by conduction through the masonry of the working space and the melting tank are 3.8 and 5.26 kW/m^2 tank area [2 – 4].

On the whole the modern structure of the furnace barriers combined with high specific extraction of molten glass 2.5 – 3.5 tons/(m^2 · day) makes it possible to decrease Q_5 to no higher than 7% of the consumption part of the heat balance of the furnace.

The data in Table 3 show that the structure of the items in the heat balance reflects a high technical efficiency of the furnace. To illustrate this conclusion the computational results for the following indicators are presented:

– specific heat consumption from the relation (1)

$$q_{\mathrm{sp}} = \frac{14496.6}{3.7} = 3918.0 \text{ kJ/kg (935.8 kcal/mole);}$$

– heat utilization factor (HUF)

$$h_{\mathrm{HUF}} = \frac{Q_1 + Q_5}{Q_{\mathrm{chem}} + Q_{\mathrm{p.air}} + Q_{\mathrm{p.f}}} \times 100 =$$

$$= \frac{14496.6 + 1523.6}{22536.3} \times 100 = 48.1\%;$$

– furnace efficiency (EFF)

$$h_{\mathrm{EFF}} = \frac{Q_1}{Q_{\mathrm{chem}}} \times 100 = \frac{9326.5}{14496.6} \times 100 = 64.3\%.$$

It should be underscored that it is desirable to increase the furnace's specific capacity, whose effect on certain heat-transfer parameters is shown in Fig. 1. The attainment of world-level energy efficiency becomes possible if the specific extraction of molten glass, whose minimum value is 2.5 – 2.7 tons/(m^2 · day), is high. This is due to not only a

TABLE 3. Heat Balance of a Flame Glass Furnace with a Horseshoe Flame with Capacity 320 tons/day and Specific Molten Glass Throughput 2.7 tons/(m^2 · day)

Heat inflow item	kW	%	Heat consumption item	kW	%
Chemical heat of fuel	14,496.6	64.32	Useful heat use for glassmaking Q_1	9326.5	41.38
Physical heat of air	7977.8	35.40	Heat losses with products of combustion of fuel Q_2	10,245.2	45.46
Physical heat of fuel	61.9	0.28	Heat losses with chemical underburning of fuel Q_3	306.2	1.36
Total:	22,536.3	100.00	Heat losses though furnace masonry Q_5	1523.6	6.76
			Neglected losses Q_{negl}	1115.6	4.95
			Imbalance	19.2	0.09
			Total:	22,536.3	100.00

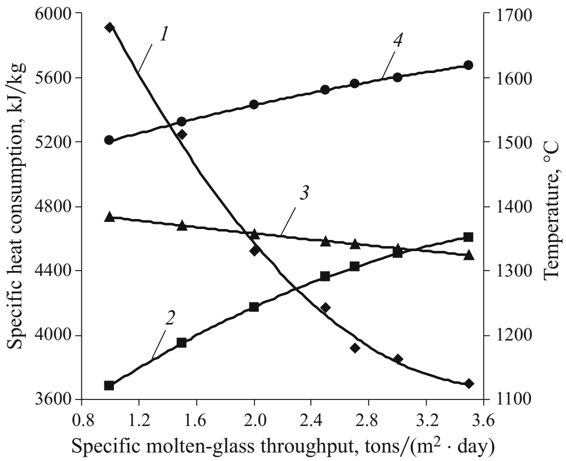

Fig. 1. Effect of the specific molten-glass throughput on the specific heat consumption for making glass (*1*), air heating temperature (*2*), average temperature of molten-glass in flow (*3*) and maximum (average over furnace width) roof temperature (*4*).

decrease of the surface area of the barrier masonry of the furnace but also the possibility of intensifying the heat- and mass-transfer processes in the melting tank [1].

The information presented in this article was obtained as a result of mathematical modeling of the thermal operation of glass furnaces. Only modern methods of analysis make it possible to use a complex, theoretically substantiated approach to the development of an object as complicated as a glassmaking furnace.

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